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A Technical Analysis of Ballistic Missile Proliferation: Introduction, Summary and Conclusions

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Arms Control Study Group

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Preface

The plan for this study was formulated in the course of several conferences held during the summer of 1965 among members of the Bureau of Science and Technology of the Arms Control and Disarmament Agency, the Office of International Affairs of the National Aeronautics and Space Administration, and the Arms Control Study Group of the California Institute of Technology's Jet Propulsion Laboratory. As a result of these discussions, this study has been jointly supported by the National Aeronautics and Space Administration and the Arms Control and Disarmament Agency. Incorporating many of the views and considered judgments of senior experienced personnel at JPL, Caltech, and also at several aerospace companies, which pioneered in the development of early ballistic missiles in the United States, the study represents a multidisciplinary approach to questions encompassing systems engineering and industrial economics set in meaningful strategic and political terms. The findings in this study are those of the Arms Control Study Group and do not necessarily represent the positions of either the National Aeronautics and Space Administration or the Arms Control Disarmament Agency or any other government agency.

This document contains the "Introduction" and the "Summary and Conclusions" of the full report. The Introduction includes a discussion of the purposes, terms of reference, assumptions, methodology and plan of the study. The Summary follows quite closely the format, subdivisions and titles included in the body of the full report, in which the points herein summarized are developed as logically and as intensively as has been possible during the 18-month study.. The conclusions present, in brief, condensed form, the essential results of this study as they appear to the authors. The two Appendixes present the summary and detailed Table of Contents of the full report, respectively.

Substantively and administratively under the overall supervision of Homer J. Stewart, the study has been a group effort, but, it is possible to assign varying degrees of individual responsibility. Sidney J. Slomich, Manager of the Arms Control Study Group, was the study leader. Albert R. Hibbs prepared the chapter on the relationships between military missiles and several types of peaceful space programs. He also wrote the section on industrial requirements, and pursuant to extensive research by John Porter, prepared the chapter on design.

Dean Kastel is responsible for the chapter on developmental functions, sequence and scheduling. Nancy Merrill organized and systematically incorporated into coherent units the remarks of the various consultants on difficulties and the value of open literature. Joseph R. Bruman prepared the descriptive compilation on ballistic missile and space vehicle components, materials and facilities.

John Hanessian, Jr. was the general editor for the study, prepared the chapter on financial requirements, and with Sidney J. Slomich, wrote the chapter on personnel.

Acknowledgment

The frontispiece photograph of "Proliferation of a Square" by the sculptor, David Green, is used with the kind permission of the artist.

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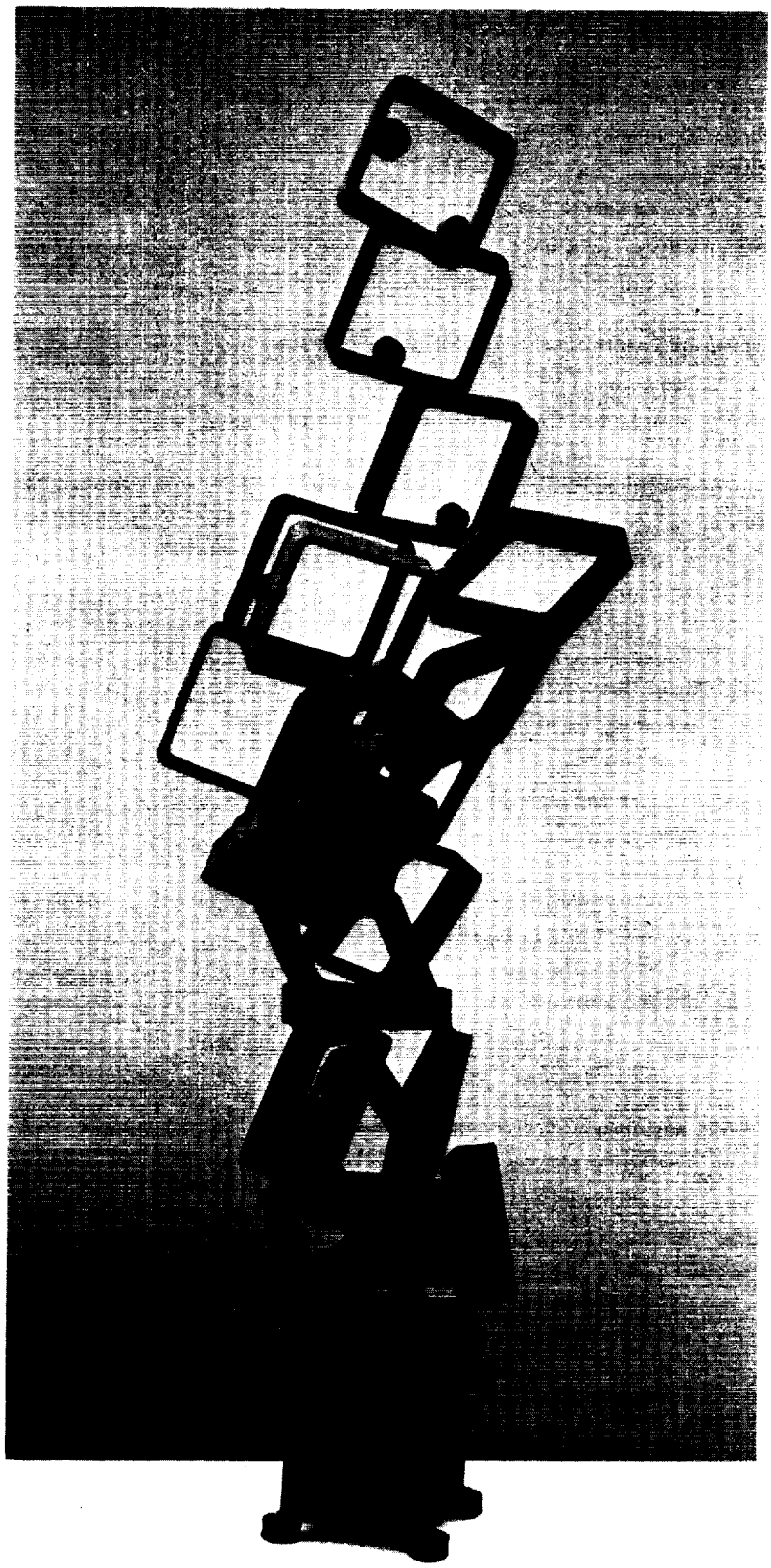

Proliferation of a Square by David Green

A Technical Analysis of Ballistic Missile Proliferation: Introduction, Summary, and Conclusions

I. Introduction: Purposes, Terms of Reference, Assumptions, Method, and Plan of Report

A. Purpose of Report

In the design and production of ballistic missile systems which might be considered for development by a "partially industrialized country," there may be critical aspects, concerning the necessary skills and resources, that may lend themselves to the establishment of controls, which are designed to inhibit or prohibit proliferation. This study, as established in the research plan developed jointly by the Arms Control and Disarmament Agency (ACDA), the National Aeronautics and Space Administration (NASA), and the Arms Control Study Group (ACSG) of the California Institute of Technology's Jet Propulsion Laboratory (JPL) has, therefore, a twofold purpose:

(1) To identify and analyze those "technical characteristics" of various "primitive," but representative ballistic missile systems (in terms of design, development and production) which a "partially industrialized country" might be able to develop in order to determine which characteristics, if any, could in a meaningful way lend themselves to the establishment of unilaterial or multilateral controls designed to inhibit the proliferation of missile systems in such countries.

(2) To perform a comparative analysis of the types of equipment, nature of industrial base, and personnel skills needed by such countries to develop and participate in various levels of peaceful space research activity, and to contrast these with the requirements necessary for the development and production of ballistic missiles. This would be done in part by comparing "the applicability and criticality of elements of space rocket systems to military missile systems," and by identifying "distinct as well as dual-purpose items.[1]"

The research plan emphasizes certain aspects for special consideration: both solid and liquid fuel systems, guidance and control problems, staging characteristics, and nature of ground support facilities. The ACSG was also asked to establish reasonable missile force sizes for the model situations of concern. For the developmental effort the Group was asked to estimate the necessary industrial resources, equipment, facilities and manpower needed to produce, deploy and support these missile systems.

The Group was further asked to identify "critical" technological aspects of the force development programs such

[1]See Appendix A of the full report.

as long-lead items, hard-to-produce components, specialized production and test equipment, and unique industrial requirements and skills.

B. Terms of Reference and Assumptions

Underlying the study's concept is widespread concern that the *genie is out of the bottle*, i.e., with the fact that rocket technology is widely and freely available and the growing possibility that lesser developed countries can accomplish within the near future, with far less cost and with limited technological and industrial capabilities, what technologically advanced countries accomplished some 15 years ago by great effort.

This concern over foreseeable proliferation of ballistic missiles is, of course, only a portion of the larger problem —the possible use (either deliberate or accidental) of missiles by a partially industrialized country to deliver nuclear warheads to a real or presumed hostile state and, in so doing, trigger off a widespread nuclear war. In this mosaic of problems only the one aspect (as noted above) is covered in this report. For a fuller appreciation of the broader problem, it is understood that reference should be made to parallel studies concerning not only the proliferation of nuclear warhead capability, but also to studies concerned with the pattern of relevant national motivations, not only in general, but with regard to specific international political problem situations.

Although it is recognized that such countries, in considering the commencement of a ballistic missile development program, would probably attempt certain shortcuts (i.e., the importation of experienced missile engineers from other countries), the ACSG has deliberately prepared this study on the assumption that such countries would rely primarily on their own initiative and resources (with the understanding that procurement of certain items would be made from the open world market and that there would be utilization of open literature).

1. Rationality, political and economic factors

Assumptions of rationality in human behavior, especially in international relations, are frequently ill-founded. Although it is far from certain that countries choosing to develop ballistic missiles will proceed in a rational and efficient fashion, it is nevertheless assumed for the purposes of this study that a partially industrialized country would not need to produce advanced and highly sophisticated missile systems. The only reasonable procedure for the ACSG has been to base the study on the expectation that such countries would rationally select the simplest, most direct, and least expensive method of design, development, production, and deployment of the least complex missile system which would satisfy their military/political requirements. Although such a missile might well be large, heavy, and relatively inefficient, it would suffice for their needs.

This report proceeds on the assumption that such a country would almost certainly be thinking of possible missile deployment against countries similar to itself (most probably a neighboring state) rather than against a major power, which has large numbers of deployed missiles, hardened sites, counterforce and advanced electronics detection capabilities.

As the terms of reference for this study are essentially technological, the ACSG has not attempted to deal—generally, regionally, or in relation to specific countries—with the relevant national political and psychological motivations such as fear, aggressiveness, a desire for deterrence capability or prestige, which might cause a given country to commence a ballistic missile development program. This report does not deal with the relevant impact of such factors as neutralism or whether and to what extent there exist throughout Africa, Asia, and Latin America significant portions of educated and/or technically trained personnel who possess the so-called puritan ethic toward work which underlies some of the more spectacular western industrial accomplishments.

As for the economic aspects of the question of ballistic missile proliferation, it is noted in Chapter IV-B (in the full report) that a modest industrial base is sufficient for the successful development of the posited ballistic missile delivery system. It is nevertheless recognized that any country proceeding to develop such a missile must have an economic/industrial base sufficiently vigorous to adjust to the requisite domestic needs, to supply the needed skills, and also, to generate the financial resources (including hard currencies) needed to purchase the necessary components and materials on the world market. Although such an economy need not be in an advanced state of industrialization, the country and its people must have sufficient technical orientation, and a certain minimum industrial capability as discussed in this study.

2. Range and payload characteristics

The Group was asked to analyze ballistic missiles having ranges "up to 1500 mi" and payloads of "no less than

1000 lb." Although no minimum range was given, the Group has arbitrarily selected 300 mi. Such a range, which requires a guidance and control system as herein described, also appears to the ACSG to be a realistic figure in terms of the political geography of today's world.

3. Accuracy requirement

Although no specific accuracy requirements were established in the research plan, the ACSG, after some study, decided to utilize for the purposes of this report, an accuracy requirement of a three nautical mile radius circle of equal probability (C.E.P.). Such a C.E.P. requirement necessitates the use of a guidance and control system, but the latter could be obtainable through the use of a radio system of minimal complexity, which is within the competence of the type of country under study in this report. It is also assumed that greater accuracy would not be necessary, given the probable political and military conditions under which the missile would be used. For example, the likelihood of hardened sites and of effective electronics countermeasure capabilities in such countries is small.

4. Force size, production and development

As the number of missiles required for deployment by a partially industrialized country against a similar and neighboring state would be far fewer in number than those which might be deployed by the major world powers, it is considered likely that a force size of 10 to 20 first-generation deployable missiles would be a reasonable assumption. These missiles could be deployed at least as much for psychological reasons as for any calculated prospect for their actual use in a wartime situation. In this study, although the 10 yr development schedule is for the first deployable missile, no firm line is drawn between development, testing and production. A deployable force of 10 to 20 missiles presupposes the preparation of a total of some 40 to 50 missiles, the balance being utilized for experimental and testing purposes.

5. "Primitive" missiles

The term "primitive" missile, as used in this study, is defined as a ballistic vehicle of basic reliability but minimal complexity, and which can deliver payloads of at least 1000 lb over distances up to 1500 mi and with an accuracy giving a C.E.P. radius of three nautical miles. The term is used to indicate a first-generation development effort. It is not used to describe a vehicle which might, in an absolute sense, be called rudimentary.

6. What is a "partially industrialized country"?

Although it would be possible to specify certain parameters (e.g., gross national product, population, industrial performance) in an effort to determine a national industrial threshold below which the program described in this study would theoretically not be possible, the ACSG has, instead, chosen to determine what is necessary for a country to produce the primitive missiles posited. *A partially industrialized country, then, for the purposes of this study, is one which, under stated conditions, can produce the missiles discussed.* In this context, however, it must be remembered that the necessary resources noted in this study are based on the requirements for the 1500 mi missile. As is explained in the report, a missile having a range of 300 mi would require less.

7. Nature of warhead

Although the study plan does not specifically indicate the nature of the warhead, the postulated payload parameter of 1000 lb, together with the assumed value of the three-mile radius C.E.P., is consistent with the use of a nuclear device. The relative merits of other warheads, such as radiological, chemical, biological or high explosive, which might be utilized in a similar ballistic missile warhead, are not a part of this study.

8. Concurrency with a nuclear warhead development effort

It is assumed that any country which undertakes to develop and produce ballistic missiles having characteristics herein outlined will probably also be concurrently engaged in a nuclear warhead development and production program. Although this study is not concerned with this parallel effort, it must be noted that it would also require material, personnel, and financial resources. The simultaneity of this effort and the concomitant strain on the nation's resources and economy should be borne in mind in any evaluation which might be carried out regarding a given country.

9. Alternative delivery systems

It is recognized that the use of alternative delivery systems, especially the use of manned aircraft which can be easily purchased on the open market, present a much less expensive means of delivery. However, questions involving the relative merits of such other delivery systems as ramjets (e.g., the *Navaho*), unmanned aircraft (e.g., the *Snark*), manned aircraft, ships, or the clandestine smuggling of one or more nuclear weapons into a country, are specifically excluded from consideration in this study.

C. Approach, Methodology and Procedure

In the process of preparing this report the ACSG has essentially utilized three parallel techniques: (1) analysis of various textbooks, monographs and articles dealing with all aspects of missile development (see bibliography in the full report), (2) searching discussions with many engineers and project personnel experienced in missile design and development (especially during the early 1948 to 1960 period) both at the Jet Propulsion Laboratory and at a number of aerospace companies in the United States, and (3) original analytical work by members of the ACSG staff (especially concerning those portions of the study devoted to development sequence, personnel and financial requirements, and the missile-space relationships chapter). Although the texts and consulting opinions were extremely valuable, especially for general perspectives, unless otherwise noted and specific reference made in a given chapter, all judgments made and conclusions drawn in this study are those of the ACSG staff.

As it is the feeling of the Group that the course taken by any one specific country may well be atypical, an analytical approach is used to determine, investigate, and describe those steps and resources necessary for any country to design, develop, and produce a "primitive" missile system as posited in this study. Rather than using an inductive or empirical approach based on what specific countries have in fact been doing, processes and associated problems are identified and elaborated to present an integrated and detailed picture. Missile building is, after all, a relatively recent phenomenon, and lessons learned from current experience may not necessarily evolve profitable insights on courses which conceivably could or ought to be taken in the future by others. In a real sense, the method is Aristotelian; that is, the ACSG has been determining and integrating patterns of phenomenon through orientation on the purpose, *telos*, for which they exist or might be brought into being. With regard to the chapter on peaceful space programs, the approach is similar—to describe and analyze in detail a representative variety of such programs, notably sounding rockets and vehicles capable of placing instrumented satellites into Earth orbit.

D. Plan of the Report

Following the two chapters incorporating the Introduction and the Summary, the report is essentially composed of three parts: (1) an analysis of ballistic missile design parameters, development sequence and schedule, difficulties, and usefulness of open literature, (2) a discussion of ballistic missile development and production resource requirements in terms of personnel, materials and components, and basic financial needs, and (3) an examination of the relationship between a peaceful space program and ballistic missile development. The implications and recommendations arising from this study are issued separately. At the end of the full report is a selective bibliography and three Appendixes, which include the Study Plan, a comprehensive List of Components and Materials, and a table cataloging the contribution of space science programs to the creation of components and facilities required for military missile systems. The three main parts of the report discuss the following questions:

1. Basic military missile designs and development process

What are the design parameters (including required missile sizes and weights) partially industrialized countries may be expected to develop, given the assumptions and exclusions established above? With which design characteristics must countries attempting to develop ballistic missiles be concerned? What, most importantly, is the range and variety of alternatives for a given mission or context?

What are the objective processes required to develop and produce missiles like those posited? What is a reasonable schedule, functionally, and what are the limitations regarding simultaneous scheduling? What are the minimum time estimates for various phases? What are the relationships among development sequence, scheduling and major difficulties which have been experienced in the past? To what extent can these difficulties be overcome by experience and the use of open professional literature? What are the limitations of the open literature?

2. Ballistic missile production requirements

What are the personnel requirements for developing the missiles postulated in terms of necessary skills and numbers for senior management, design and supervisory personnel, senior engineers, junior engineers, skilled technicians, unskilled personnel and administrative support?

What are the basic facilities and components, subcomponents and assemblies necessary to produce missiles generally? How may they be obtained on the open market? Do they have uses in other products and industrial processes?

What in general is the industrial level necessary for a country to achieve before it can realistically be expected to undertake the programs discussed above—i.e., which industries would it need, what types and level of educational system, technician apprenticeship programs, etc.?

What financial resources are necessary over the postulated period to design, develop and produce successfully the ballistic missiles described in this study?

3. Relationships between missiles and space programs

What are the relationships among design, development and production requirements for the military missiles, on the one hand, and a variety of typical, peaceful space programs, on the other, e.g., various types of sounding rockets and rockets capable of placing into Earth orbit instrumented satellites–for the purpose of determining the extent to which capabilities for conducting these programs constitute meaningful steps towards military missile development and production capabilities? How much of a step forward is each type of peaceful space program?

II. Conclusions

A. An Overall Statement

Any ballistic missile has a vast number of interrelated parts. Given the current widespread availability of many integral components and of relevant technological information, the development and production of these parts do not present insurmountable difficulties. None requires a level of technology which might extend beyond the reach of a partially industrialized country–even one without previous missile development experience. If a given country of this nature should begin such a development program with its own initiative, and relying primarily on its own resources, its directors must, however, recognize the criticality of certain aspects, e.g., the importance of compatability of all component units.

In addition, although a degree of concurrency is highly desirable, it will be limited by experience and by the availability of component systems. Thus, although specifically necessary material, personnel and financial resources are finite and measurable, the primary problem will be the accumulation and application of the skills necessary for this program. The crucial elements, along with strong political motivation and national commitment, are persistence and application to a long-term developmental process of gradually acquired skills, technological expertise, and physical resources. There will be a necessary path of continuous experimentation, testing and proving out of a specific design, which it is judged would require at least 8 and more likely 10 yr to complete the development of a ballistic missile having performance characteristics as posited in this study adequate to carry a 1000-lb payload over distances up to 1500 mi and deliver it to a target within a three-mile radius C.E.P.

B. Missile Design Parameters

The overall missile configuration expressed by such parameters as weight, shape, and number of stages, are fixed within reasonable limits by the laws of physics and chemistry, and by widespread engineering developmental experience. With the given specifications of payload, range and accuracy, a number of alternative missile designs are feasible. These include choices in propellant, guidance and control techniques, and in the selection of materials. Either a solid or liquid propulsion system is suitable, each having given advantages and disadvantages, and the assumed accuracy requirement implies the use of a guidance system, which can be either radio or inertial. While a radio system is easier to develop, because of the greater availability of components, there are other factors which might lead to the selection of an inertial system–either later in the development process, or for second-generation systems. While many different designs are feasible, the overall quality of a specific design choice, its aptness for the country, and, above all, its execution is of basic importance. A *soft* operational site is assumed.

C. Development Schedule

Assuming no previous experience or capability directly in the field of ballistic missile development, but given the dedication, necessary resources, and continuity of budgetary and political support, it is concluded that ~8 and more likely 10 yr would be required from the initiation of the project to successful deployment of the first of useful military weapons. This schedule, which assumes the use of the considerable open literature and many commercially available materials and components, is in reference to the 1500-mi missile, which is the one primarily discussed in this study. For a 300-mi missile it is likely that a saving of 2 yr development time could be achieved.

It is recognized that a given country, embarking on such a program, would be very much interested in exploring possible methods for reducing developmental time. Certain advantages would obviously be gained if, for example, the project directors were able to import from the outside an experienced design team, or if the country had within its borders an aircraft assembly plant, or were engaged in certain aspects (e.g., large sounding rockets) of a space research program. It still remains necessary, however, for even the most favorably situated country to go through the objective patterns of missile development and testing, as part of the task of proving out a new, individual design. It is doubted whether even relatively advanced countries

could, under the best of circumstances, and with a generous share of good fortune, cut more than 2 yr from the 8 to 10 yr minimum period, unless they possessed functioning teams which had actual experience in the development and manufacture of large rockets.

D. Development Sequence

Engineering experience in the United States indicates that little if any deviation is possible from a typical development sequence, which is carefully described in the body of this report. Nevertheless, some shortening of the schedule can be achieved by increasing the degree of concurrency in development work on the various missile subsystems. If a country can afford this procedure, which makes good sense from an engineering point of view, there are obvious time advantages to working out alternatives simultaneously, rather than serially.

E. Difficulties

Despite the large volume of open literature, there are a number of difficulties which should be expected in any missile development program. The development schedule utilized in this study, therefore, does take into consideration an average number of difficulties. Perhaps the most important of these is inherent in the developmental process: successful systems integration of a design which is by its nature new. Missile development is more an art than a science, and every design, no matter how good in concept, will develop problems. Some of these include combustion instability in the engine; unstable interaction between the guidance and control system and/or the propulsion system and the airframe; the need for an adequate environmental model and test procedures; and the injector design for a liquid propellant engine.

F. Usefulness of Published Information

A large quantity of information on missile design and missile production techniques has been published in the open literature. Without the availability of this literature, many additional years would probably be added to the development process. The fact of its existence may also play an important role during a feasibility study. However, this information is of selective use, and usually does not contain descriptions of mistakes which have been committed in specific missile programs. It must be noted that each missile development program will include a large variety of problems, the solution of which will require experience, persistence, continuity of effort and patience, rather than reference to a text. Finally, it must be emphasized that optimum use of this literature requires the availability of librarians trained in information retrieval and abstracting procedures.

G. Personnel Requirements

For the 1500-mi missile, a staff of ~3600 would be required. Some 60% of these would be technical, ranging from senior management (5), through the engineering groups (314) to skilled technicians (1070), and finally semiskilled and unskilled labor (800). The half dozen men in senior management, including the technical director, and also the chief designer, would be the key individuals in the program. It must be noted that in a partially industrialized country, with limited technical personnel resources, there would be a severe problem in the recruitment of the necessary large number of skilled technicians, especially with the expected concurrent program in nuclear warhead development. Although the greater the degree of previous rocketry experience, the greater will be the degree of effective concurrency and the less the time and expense, it must be emphasized that an important conclusion of this report is that a few talented versatile, imaginative engineers, with a special flair for translating physical functions into engineering devices, and having a talent for organization of men and material, can satisfactorily design and develop a ballistic missile even without any specific ballistic missile design or production experience. It should be noted that even partially industrialized nations can be expected to have at least a few individuals with these capabilities. As noted above, missile development is to some extent a learning process, and the process itself can help generate necessary skills and expertise.

H. Material and Industrial Requirements

Provided the necessary hard currency is available, the great majority of components and materials required can be obtained on the open commercial market. Most of these items have standard commercial applications. Those few items, which must be specially constructed for the particular missile design, can be manufactured with tooling which is also available on the world market. Thus, the specific requirements of industry and component availability needed within a country can be relatively small and can correspond to light industry and certain manufacturing skills and production techniques (such as quality control), rather than a broad industrial base. This assumes an economy sufficiently vigorous to absorb whatever internal strain which may be necessary to prosecute the program.

I. Financial Requirements

Assuming a 10-yr development period and an optimum use of personnel, it is expected that personnel costs for the 1500-mi missile would be within the range $100 to $200 million (with a typical figure of $180 million), depending on the given country. These figures assume maximum domestic wage levels (which, however, can be expected to be substantially less than in a fully industrialized country) and also assume that some personnel, brought home from overseas, would demand and receive even higher salaries.

Past United States experience in comparable missile programs indicates that costs relating to facility construction and maintenance, materials and components, can be expected to vary from $250 to $700 million (with perhaps $350 million as a typical figure). Since these latter figures would also apply, in an absolute sense, to a partially industrialized country, it is thus estimated that the cost of the entire program will lie within the range of $350 million to $900 million, with perhaps $530 million being typical, if one assumes the typical nonpersonnel cost figure and the typical personnel expense figure. Assuming two additional years for the production of the assumed force size, an additional financial burden of perhaps $30 to $50 million should be expected.

These figures indicate the prosecution of an efficient program, but give an allowance for mistakes and difficulties. As indicated earlier, the cost would be somewhat less if a 300-mi missile were posited, or if development time was shortened through the importation of nonnational personnel for certain key positions.

J. Relationship of Peaceful Space Programs to the Development of Military Missile Capabilities

Any activity in the area of scientific space program developments carried out within the country will provide an increase in required skills and make available certain necessary components and materials for a military missile development effort. The degree of this effect depends upon the particular space program undertaken.[2] The development of scientific instruments to be launched on rockets provided by another country would make a small and almost negligible contribution, whereas the development of a domestic satellite launching vehicle would be almost equivalent, as a technical achievement, to the development of a military missile. The breakpoint between these two extremes appears to be a development project for a large sounding rocket which would probably result in fulfilling about half the requirements for both skilled personnel and special components and materials.

[2]See Table 4, page 24, of this report.

III. Basic Military Missile Designs

A. Model Parameters

Given the assumptions and exclusions established in the introductory chapter, it is necessary to inquire into the design parameters of simple missiles partially industrialized countries are likely to develop. This study, therefore, discussses the design of a group of missiles for various ranges which could be typical of what these countries would select, were they to follow a simple, direct, and basic path of missile development.

Two missiles of this group have a range of 300 nmi; three of 1500 nmi. Two utilize solid propellants, whereas three utilize liquids. Two of the three liquid propellants employ nitric acid as oxidizer, with hydrazine as an additive; the other posits the use of liquid oxygen. Three incorporate two stages, whereas one has three and one has a single stage. All designs could incorporate a guidance system, which can be either radio or inertial. Table 1 describes the basic parameters of these five missiles.

B. Representative Characteristics of the Model

It is recognized that those missiles which partially industrialized countries might actually build would differ in many details from the designs described here. However, given the drive for the utilization of simple methods of achieving the goals of range, payload, and accuracy, engineering experience and the laws of physics and chemistry generally require the evolution of missiles like those herein described.

1. Staging

High performance missiles, that is, missiles intended to carry large payloads over long ranges, often use more than one propulsive stage. This has the advantage of savings in overall missile size and weight. Less fuel is needed than would be used in a single-stage system, since some of the dead weight (engines and empty tanks) can be jettisoned during the propulsive phase. In general, the more stages used, the greater the weight saving. However, it should be noted that the optimum number of stages must be selected with due consideration of the additional system complexity which each additional stage represents.

Table 1. General characteristics of five selected ballistic missile models

Characteristics	Model 1	Model 2		Model 3		Model 4		Model 5		
Number of stages	one	two		two		two		three		
Range, mi	300	1,500		1,500		300		1,500		
Propellants	(Liquid) Nitric acid plus hydrazine RP-1	(Liquid) Nitric acid plus hydrazine RP-1		(Liquid) LOX, RP-1		(Solid) $(C_2H_4O)_n$ and ammonium perchlorate		(Solid) $(C_2H_4O)_n$ and ammonium perchlorate		
Specific impulse, sec	228	228		253		239		239		
Stage	1	1	2	1	2	1	2	1	2	3
Over-all diam., ft	4.4	6.3	2.8	6.1	2.8	3.3	1.8	4.1	3.2	1.8
Over-all length, ft	34.5	57	24	56	24.5	33	16	60.5	34.5	19
Weight at ignition, lb	29,500	87,400	9,400	61,900	7,900	16,650	4,150	54,900	14,900	3,900
Weight at burnout, lb	7,128	21,568	3,520	17,350	3,346	7,650	2,386	22,500	7,200	2,305

The designer, therefore, would attempt to achieve a balance between the complexity of increased numbers of stages and the weight penalty associated with fewer stages.

2. *Propellants*

There are many possible choices of propellant. In the United States, a variety of alternative but equally suitable approaches in various contexts have been utilized. The fact that particular engineering solutions have been chosen for the models does not mean that these are the only solutions or even necessarily the best, for final choice rationally depends upon the availability of materials, capabilities of the development staff, and similar factors.

To illustrate, the most important parameter characterizing capability of a propulsion system is specific impulse (I_{sp}). This is the impulse, usually measured in lb-sec, applied to the rockets in the combusion of 1 lb of fuel. There are in existence a number of basic, reliable, liquid propulsion systems with specific impulses in the range of 225 to 275 sec. There are also a number of relatively simple solid propulsion systems with a specific impulse in the range of 200 to 250 sec. There are propellant combinations exceeding the upper limits in both categories, but their use requires a comparatively advanced degree of development. Therefore, although it is not possible to determine which specific combination will be selected for any particular application, it can be safely asserted that the propulsion system will have a specific impulse differing only slightly from those of the systems herein described.

Regarding the calculations in setting up the models with the I_{sp} range discussed above, the specific choices of fuels were made after examining factors of cost, availability, degree of corrosiveness or instability, and compatibility with relatively simple and generally available oxidizers. Typical of such liquid fuels are aniline, hydrazine, alcohol, kerosene, and gasoline. Certain advanced fuels such as liquid hydrogen and still unproven oxidizers like liquid fluorine have been excepted as being too difficult to handle.

There are two broad categories of solids — castable and extruded. Castables are generally composed of materials such as asphalt or rubber, which liquefy when heated or become solid on polymerization, and can be mixed with a powdered oxidizer. The shell of the rocket is the mold with a flexible liner usually used for bonding the propellant to the metal casting. Extruded formulations offer somewhat higher performance than castables, but their manufacture is impractical for large motors. Therefore, the solid fuel example chosen is a castable propellant: rubber, with ammonium perchlorate being the oxidizer. These are basic materials which have the advantage of easy availability and low cost.

Since liquid propellants are significantly more efficient than solids, fewer stages are needed for the same overall missile weight. Only the fifth model, the solid-fuel, 1500-mi rocket involves a third stage.

3. *Propellant choice and upscaling*

One of the most difficult problems in the development of rocket engines is the extrapolation of data, no matter how carefully and systematically executed, obtained on small experimental models to full-scale engines. The essence of the effort is not so much in the selection of

the proper propellant (provided that those most obviously unproven are not selected) as in the development of full-scale engines which will burn, with the propellants chosen, in a stable manner at the required level of thrust and for the required duration. Thus, the selection of the propellant, provided it is suitable in terms of the natural resources of the country or the availability of necessary materials abroad, and provided that its performance is suitable for the design undertaken, is relatively minor compared to the execution of the total design of the engine and its interaction with all other parts of the missile.

4. A note on clustering

In connection with discussions on proliferation, an important question arises concerning the possibility that countries with access to small sounding rockets may be able to avoid difficult developmental problems by clustering a number of small solid-propellant engines – that is, binding them together so that they can be fired simultaneously, providing, thereby, the thrust of a large rocket. While clustering is more suitable for extremely large vehicles such as those used in space exploration, this approach is not considered likely for use with military rockets as discussed in this study. For example, if several small solid engines are clustered, variations in ignition and burning characteristics will cause problems for the guidance system. With regard to liquids, the potential advantages of clustering tend to be more than offset by the added complexities of propellant flow control.

5. Launch site configuration

Consistent with the assumption of a "primitive" missile design, a *soft* launch site configuration is presumed. Most of the problems of design and construction of such sites would be worked out in the development of the test range facilities. Troop training and other purely military activities would pose the principal additional demands during the deployment phase.

C. The Range of Design Alternatives

Having established the models and the basic considerations relating to size, weight, and choices of fuels within the range of relevant physical laws and proven engineering experience, it may be expected that a great degree of similarity in size, weight, and staging would be found, should partially industrialized countries logically go about developing simple missiles for similar ranges and payloads. Nevertheless, the task of establishing technical controls will always be complicated by the fact that there are many possible variations in design. Figures 1 and 2

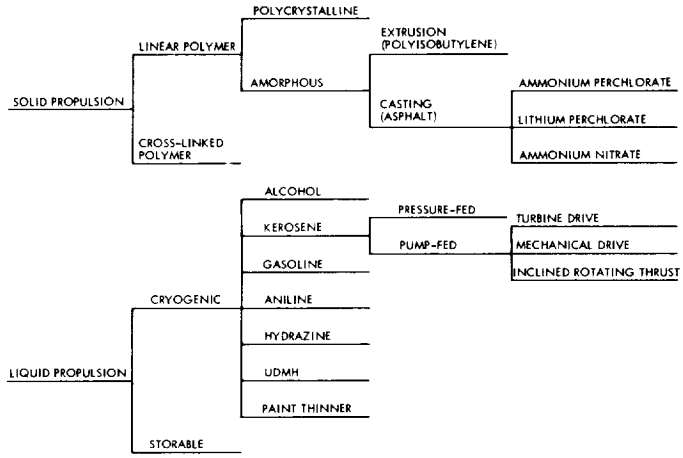

Fig. 1. Scheme of design choices in the selection of a propulsion system [3]

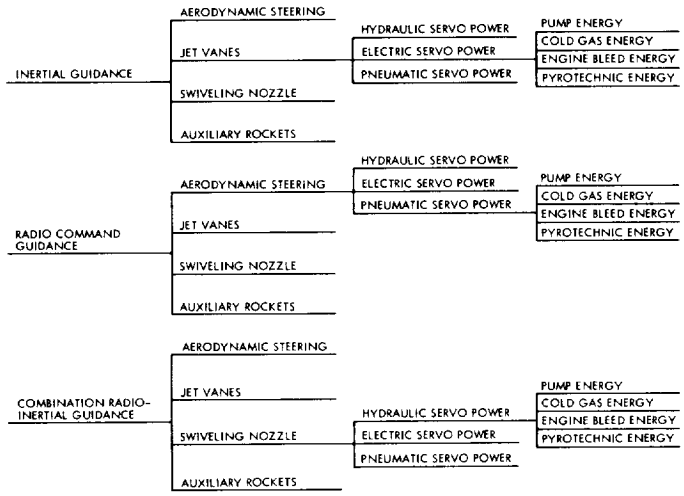

Fig. 2. Design options for the choice of a missile guidance system

illustrate only a few of the variations possible, in one case with fuels and in the other with guidance systems.

IV. Development Functions: Schedules and Time Estimates

A. A Note on Self-Criticism Among U.S. Missile Designers

It does not appear possible to discuss the development, by a partially industrialized country, of first-generation

[3] The course of decision moves from left to right. Only one representative path through the process is indicated. All lines which terminate should be considered to have a similar set of design options following them, which have been left off this figure for the sake of simplicity.

or "primitive" missiles with individuals who participated in a meaningful way in the early problems faced by American missile engineers without hearing statements like, "They don't have to do it the way we did," "We make it hard for ourselves," "We use too many people," etc. It is apparently natural for those individuals who contributed heavily to new, pioneering, industrial processes, with all the dead-ends and trial and error necessarily experienced, to look back and calculate how they could have done it differently and better. It seems that the more able the man, the more successful in overcoming scientific, engineering and management difficulties, the more prone he is, with the benefit of hindsight and successful accomplishment, to say that what was done (in perspective rather well) could have been done much better, at much less expense and much more quickly.

It may be the case, but there appears to be no logical reason why, without the wisdom of hindsight and successful accomplishment in overcoming difficult design and production problems in a new field, there is any reason to believe that missile design, development and production in partially developed countries, if undertaken, will be free of organizational problems, less than optimum design, at least partially faulty execution of plans, indiscriminate recruitment, personnel hoarding, restrictive labor work rules, poor coordination with political authority, less than perfect planning or simple human error. Common sense and experience would indicate *a priori* that all of these will occur to some extent in lesser developed countries attempting to design, develop and produce ballistic missile delivery systems. At the same time, they will not occur to the same degree in all instances, and a prudent assessment of possibilities cannot count on their occurring at all.

B. Objective Patterns of Missile Development

Despite all the talk about doing things differently and taking shortcuts, there remains the fact that there is an objective pattern in missile development; these patterns must be followed if desired ends are to be achieved. If they are ignored, there will be many more mistakes than necessary, more explosions and fires than those which are unavoidable, more expenditure of time and money, and, in the end, there may be no usable missile. It is essential to state that in the systems engineering approach, as exemplified by military rocket development, the requirements for an objective, structured flow of events, dynamically interrelated in time and space with all others *is* the process. Occasionally U.S. missiles, developed during the 1950's, are described as "simple" or "primitive." They may merit these adjectives in a historical sense, but actually they are neither simple nor primitive, and the systems engineering approach required for their development is among the most demanding ever devised.

C. Development Program Schedule

A partially industrialized country starting from the beginning of the design and development process could, given the several assumptions noted in this study and with reasonable fortune and efficiency, develop and have ready for deployment the first of the 10 to 20 missile force of the 1500-mi type postulated in the preceding section in 8 but more likely 10 yr. Similarly, the first 300-mi missile could, with the same qualifications, be ready for deployment in 6 to 8 yr. This estimate is based upon historical examples augmented with an analysis of the time and effort required to bring to fulfillment the interrelated phases in large military rocket development under study here. Figure 3 illustrates this schedule in its main components for the 1500-mi missile. For the 300-mi missile, a similar development schedule can be envisaged by reducing the last 8 yr of the illustrated schedule by 30%.

The scheduling, as portrayed, is the most direct, expeditious and orderly path, but there are some risks because some concurrency in development activities is assumed, as well as a degree of management skill. It would be much simpler if several or many of the functions were developed serially – one after the other – because of the problem of compatibility and systems integration. The approach throughout this study is consistent with the concept of a continuous concentrated effort necessary to accomplish the desired ends in a practical but expeditious manner.

Fulfillment of a schedule with the indicated degree of concurrency requires successful implementation of designs in all phases in an orderly, planned process. A major slippage in an important function, particularly propulsion, could throw the entire effort out of phase. If, for example, prototype propulsion development is not completed according to the deadlines as indicated on the chart, the entire flight test program and subsequent redesign are delayed. Furthermore, should the prototype guidance and control system be retarded in its development, such that its completion is not reached by the middle of the eighth year, its introduction into the flight test program is delayed, along with the testing of all the major components in themselves, and in their working interrelationships with others. Nevertheless, the 8 to 10 yr schedule, selected for detailed discussion in this study, does allow for anticipated difficulties and is considered reasonably sufficient. It is possible that some aspects of the

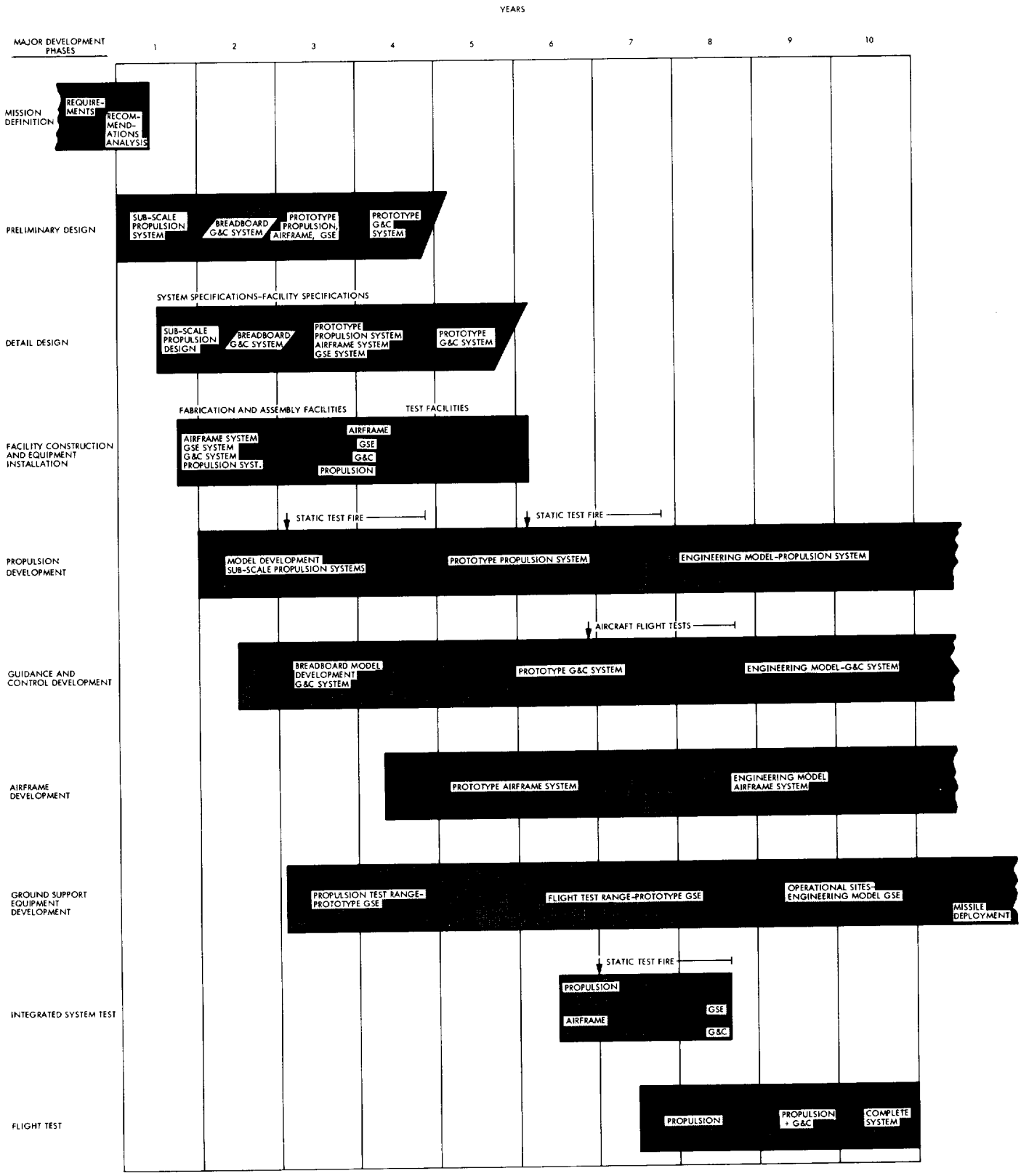

Fig. 3. Development program schedule

development program will be completed ahead of schedule. If so, this would probably not result in any shortening of the total effort, since development work on other subsystems must still proceed. Instead, such a situation would make available some additional manpower who could be used to increase system reliability.

Another graphic way of looking at the problem of missile development is in terms of the necessary breakdown of events or functions which must be performed in dynamic interrelationships in a multitude of test programs modifying and constantly requiring design changes. This is indicated in Fig. 4.

After typical functions or events, as specified in the box on the extreme left (Fig. 4), concerning mission definition, are executed, the preliminary and detailed designs are completed and the development process proceeds into phases in which are prepared the detailed specifications for the various systems and facilities necessary to produce them. Development then becomes a process in which reciprocal interrelations of a wide variety of functions proceed (concurrently with ongoing tests) through stages of fabrication, subassembly and assembly. Functions, because of their interrelationships with others, may have to be modified or totally reworked. This is the reason for the double direction of the flow lines on the chart. Further, the integrity of each particular function, as well as its interrelations with others, must be achieved and maintained. Materials and electronic components must adequately perform as well as properly interact with other integral parts of related systems and subsystems.

The chart also illustrates the process which takes place within each phase and subphase of development in a manner indicating typical types of hardware (materials, components, subcomponents, assemblies, etc.) which may be involved in such phases. There is no way to avoid these functions, and if one type of hardware is not used, another must be substituted for it. There are few acceptable shortcuts around the necessary pattern of ballistic missile development.

V. Difficulties

There is little doubt that developers of new military missiles, of the types postulated, in partially industrialized countries or, for that matter, in relatively advanced countries, will run into a number of difficulties. Engineering experience, as well as objective analysis of the process, indicates that certain kinds of problems, by the very nature of rocket development, are likely to occur or recur. It must be stated, however, that *none* of these difficulties is insurmountable. Redesign and engineering solutions to all difficulties can ultimately be reached through the application of enough skill and effort. The quality of management and engineering experience will be an important factor in the resolution of such difficulties. Further, difficulties could not only mean greater expenditures of funds and personnel, but could involve possible loss or diminution of government support. The illustrative problems described below are included to reflect this pattern of thought.

A. Design Problems

Every missile which is not an exact copy of another and executed according to the exact specifications and using exactly the same material is new. Every new missile will have built-in *bugs*, because of unavoidable mistakes in the design. In some cases, these errors will be discovered during component fabrication or the assembly of subsystems. In other cases, only flight testing will reveal the problem. In most cases where the error was in the original design, considerable time will be lost in the process of correction. It is a major purpose of the development test program to discover these difficulties quickly.

B. Liquid Propulsion

1. Compatibility of materials

Problems in this area usually arise in the selection of materials for gaskets and other non-metallic substances.

2. Combustion instability

Burning characteristics are dependent upon particular injector and combustion chamber designs and propellant compositions. Since the exact burning characteristics of any new design cannot be accurately predicted, considerable trial and error is necessary, and some explosive failures can be expected. There will always be difficulty in upscaling models.

3. Cooling

For liquid engines, experience indicates that regenerative cooling is less demanding of advanced technology than refractory or ablative materials in chambers and nozzles. Although such information is available in open sources the designer in the partially industrialized country is still not without his troubles. The shape and size of the passages of the workable regenerative cooling system are difficult to design, with special tooling and welding skill required for their fabrication.

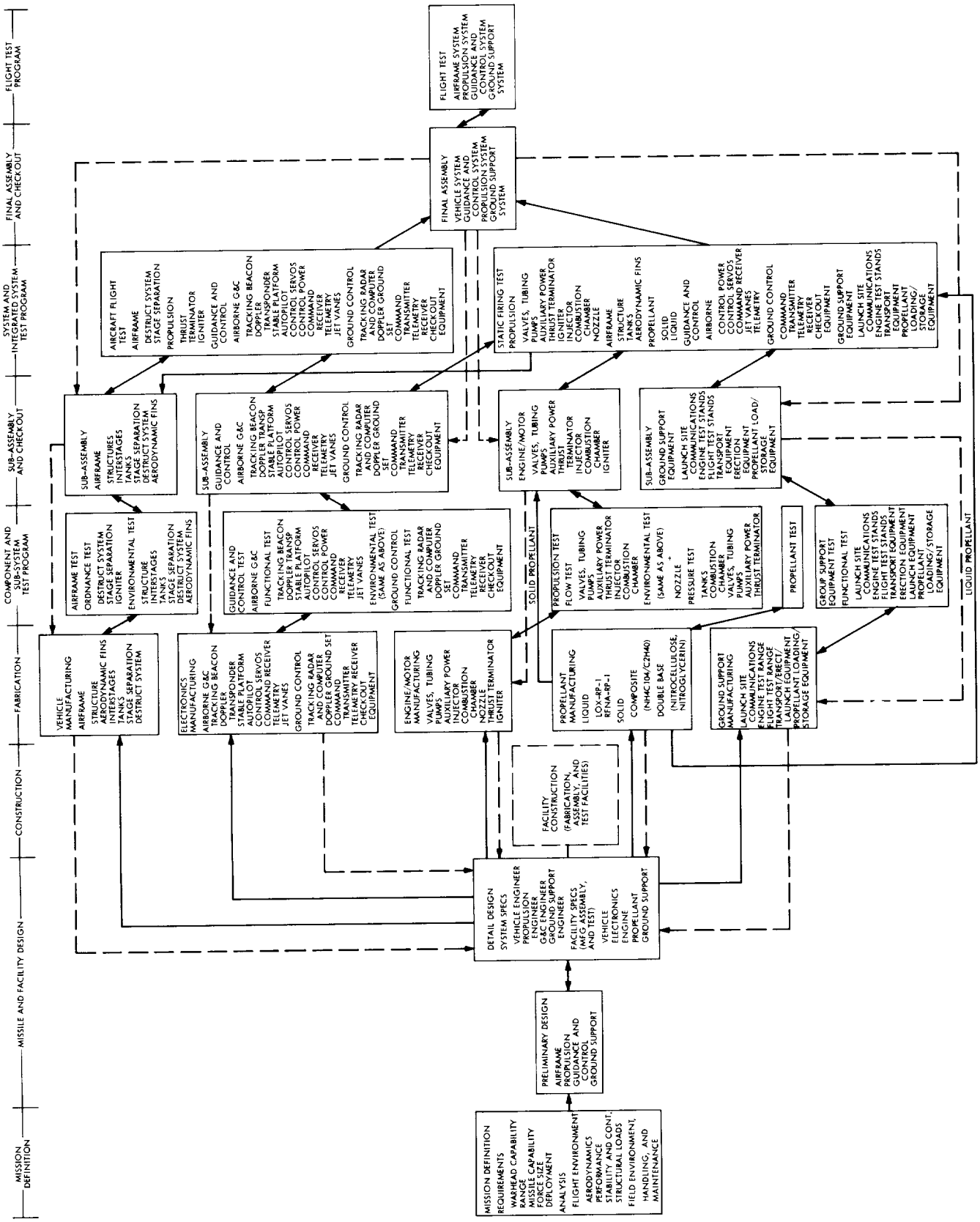

Fig. 4. Missile hardware development sequence

4. Plumbing

Intricate plumbing in liquid propulsion systems cannot be avoided. Feed pumps and valves are difficult to conceptualize and fabricate. Feed systems, such as turbopumps, are not easy to develop, and the selection of a design which can be fabricated in a manner which will be compatible with the entire system is demanding. Thrust termination, especially the development of suitable valves, stands out as a critical precision operation.

C. Solid Propulsion

1. Thrust termination

Thrust termination is even more difficult in solid fuels; significant energies must be expended, but without affecting direction or speed of the payload, or damaging it.

2. Nozzles

Suitable nozzles, which are not easy to design for liquid-fuel systems, are more difficult to develop in relation to solid-fuel systems, because the higher molecular weight of solid propellants produces a much higher burning temperature. This in turn generates requirements for the special materials and skills in high-temperature metallurgy, design and fabrication of both the throat and nozzle. Unpredictable flow characteristics and erosion effects, which can be discovered only in full scale tests, will result in some expensive trial-and-error development work.

3. Bonding and storage

Bonding, grain integrity and separation of the propellant from the liner are always problems and could prove serious in certain environments, notably warm, humid climates.

D. Guidance and Control

1. Inertial guidance

Basic components, e.g., stable platforms, gyroscopes and accelerometers, are extremely complicated and require a very high degree of precision and skill in manufacturing, as well as the availability of precision tooling.

2. Radio guidance

The easiest and most rational guidance option, when jamming is not a problem, is to use the radio guidance system. While the parts are standard, easy to procure, and not even particularly difficult to manufacture, integrating them into a functioning system compatible with the rest of the missile is a difficult process for either a radio or inertial system. Some in-flight failures must be expected.

E. Systems Integration

The coordination of complicated parts into a functioning whole is an integral and difficult aspect of the developmental process. Integration takes place on two levels: the coordination of personnel, subcontractors, and concurrent component developmental efforts, in a managerial sense, and integration of the separate components and subsystems into a functioning missile, in the engineering sense. One can say *a priori* that even if the missile design and specifications are suitable for the particular country and the result of a first-class effort, interactions which cannot be foreseen in advance will occur. Guidance and control characteristics may interact in an unstable manner with aerodynamic characteristics. The propulsion system may create a damagingly high level of vibration. Even the cables which carry power to various electrical components may not fit in the missile structure, etc.

F. Quality Control

The reliability of the missile is determined by the quality and uniformity of its components. A respect for quality control, especially during the production phase, must be instilled among technicians and engineers. Historically, it has emerged only through patient and experienced application. Uniform assembly procedures and systematic inspection techniques are necessary as well as reliable instrumentation for quality control. Absolute uniformity in operations, components manufacture and tests is essential, not only for flight testing but also for the production of the 10 to 20 missiles to be deployed. If telemetry data is not returned from properly calibrated instruments and reliably and uniformly reduced, it will not be possible to determine causes of malfunction or inadequate performance in flight. Thus, redesign would be delayed or inhibited. Additional flight tests would be required, with associated schedule delay.

The equipment on board a ballistic missile must be engineered to operate over a significantly wider range of environmental conditions than in any similar operation such as jet aircraft. Designers and developers may, for example, experience surprises in vibration technology, acceleration and vacuum phenomena. Voltage breakdown, e.g., can occur under a variety of circumstances at altitudes above 100,000 ft. Controls tend to respond differently as the vehicle passes through the sonic barrier. Even ordinary environmental conditions may pose obstacles: precision

welds can be adversely affected by humidity, temperature variations, dirt, certain oxides, and even almost imperceptible physical-chemical changes within certain alloys.

VI. The Potential Usefulness of Published Information

A considerable amount of information on missile technology, such as textbooks, handbooks, monographs, and proceedings of space technology conferences has been published in the United States in a form easily available to engineers in other countries. Additional material has been published in a number of journals which have wide circulation. Still other relevant reports are published by various governmental agencies and their contractors which, though unclassified, may be somewhat more difficult to obtain by foreign nationals. A number of publication on missile technology are also available from the U.S.S.R. and other countries. Only very advanced propulsion technology is not covered extensively in the unclassified literature. Other useful sources of information are sales brochures which often include considerable detail on specification and performance of items like gyroscopes, common autopilots, inertial platforms and accelerometers. There are good, basic descriptions of certain difficult problems, such as thrust termination. Basic materials technology is well covered, as are general concepts for developing nozzles and throat liners, difficult areas indeed for both liquid and solid propellants. There is literally a vast amount of open information available on test facilities and test techniques.

This unclassified accessible literature can, in several ways, simplify the task of developing a new military missile system. First, the decision to proceed with a recognizably difficult technological program can be arrived at with more assurance given the knowledge that such programs have already been undertaken by others and that a considerable amount of descriptive literature on these projects is available. Second, feasibility studies and preliminary design work can proceed much more rapidly and with much more assurance of correctness by making use of ample data in published literature describing in general terms the design of successful missile systems. Third, in certain technical areas, detailed information is available on techniques and materials which could act to save considerable development time by directing engineers along paths of work which have already proven successful.

At the same time available open literature does not provide all the answers, and various limitations must be noted. A considerable degree of engineering background is needed to utilize effectively the large amount and widely scattered information which has been published. In addition, since much of the design and fabrication required for successful missile development is more of an art than a science, it has not been reduced to written descriptions. There are some procedures which can be successfully completed only by trial and error, and furthermore, each new missile design has its unique problems which cannot be resolved by reference to descriptions of other missiles, no matter how detailed. In this regard, it is noted that the literature seldom contains descriptions of mistakes, or dead-end development efforts. This omission is important, for such descriptions would mark out areas which should not be traversed, and also could transmit a feel for the experience gained in actual missile development. A number of specific illustrative examples are presented in the main body of this study.

Engineers without experience in missile development, further, might possibly use open sources in a counterproductive manner by selecting and rigidly adhering to a particular approach, proven out in a particular case, but perhaps inapt for their design. They could easily build into their program severe and unnecessary difficulties. Finally, it must be emphasized that optimum use of this literature requires the availability of librarians trained in information retrieval and abstracting procedures.

In summary, although open literature will not give specific *cook-book* instructions for missile design and fabrication, a first attempt at a missile development project, without thorough use of this literature, would take many more years than the 8 to 10 yr effort described in this report.

VII. Personnel Requirements

A. Relationships with Time, Scheduling, Expense and the Utilization of the Open Literature

As already indicated, by its very nature there are a number of *built-in* difficulties intrinsic to the development of new ballistic missiles. The extent to which these difficulties are successfully solved, and components well-integrated into a functioning system will depend to a very great extent on the evolution of an efficient, highly-motivated management team and engineering staff.

The greater the efficiency and the higher the degree of development experience of senior management, design and supervisory teams, the greater will be the degree of

Table 2. Personnel categories and requirements

Categories	Requirements					
	Labor, unskilled & semi-skilled	Technicians, skilled[a]	Engineers, Jr.	Engineers, Sr.	Management, Sr.	Total
1. Senior management and technical director	—	—	—	—	5	5
2. Design staff	None[b]					190
(a) Vehicle	—	25	15	7		
(b) Guidance and control	—	25	15	8		
(c) Propulsion	—	25	15	7		
(d) Ground support	—	25	15	8		
3. Fabrication						1190
(a) Vehicle mfg	35	40	20	5		
(b) Elec. sub-units	100	100	80	20		
(c) Engine development	90	90	15	5		
(d) Propellant mfg[c]	120	120	25	5		
(e) Ground support mfg	200	100	15	5		
4. Test program						396
(a) Airframe	10	30	3	1		
(b) Guidance & control	10	100	4	1		
(c) Propulsion	10	80	3	1		
(d) Propellant	5	10	3	1		
(e) Ground support equipment & range operations	20	100	3	1		
5. Assembly and checkout						408
(a) Airframe	50	50	1	1		
(b) Engine/motor	50	50	1	1		
(c) Guidance & control	50	50	1	1		
(d) Ground support	50	50	1	1		
Subtotals	800	1070	235	79	5	2189
6. Administration[d]	600[e]	700[f]	120	30	—	1450
Subtotals	1400	1770	355	109	5	3639
7. Facility construction[g]						1000

[a]This includes welders, toolmakers, electricians, junior draftsmen, mechanics, lathe operators, and chemical handlers.

[b]Any unskilled laborers required here would be utilized from the fabrication group.

[c]These figures are included *only* when the missile program requires the *manufacture* of the propellant. As discussed in the text, if the propellant is purchased, the only personnel needed would be for transport, handling, and storage.

[d]The total administrative personnel figure represents 40% of the total. Depending on the conditions faced in a specific country, this figure may be 50% or even higher. Although a breakdown is not specifically suggested in this table, it is assumed that the administration services will be subdivided into the following four units: financial management, procurement, personnel administration, and material services.

[e]This includes all white collar clerks, as well as blue collar personnel, in material services and plant maintenance.

[f]This includes all stenographic personnel, librarians, photographers, etc.

[g]The facilities construction personnel requirement is one of short term. Once the facility construction is complete, the need for these personnel will practically cease.

effective concurrency; that is, the development and building simultaneously of guidance and control, propulsion, air frame and ground support, along with their integration into functioning systems reflecting effective and apt designs. Also, the more effective the management and the greater the degree of experience in rocketry development, along with its effective utilization, the more likely will it be possible to keep down costs, as well as surmounting difficulties posed by or built into even the best designs.

But this is not all, for more than senior management is essential, and more than actual rocketry development experience desirable: all aspects of time, scheduling, experience, use of literature require for their successful resolution a core of experienced and capable senior engineers, a very large group of skilled technicians, a group of sound junior engineers, a corps of semiskilled and unskilled labor, and administrative support—all welded together by senior management into a smoothly functioning team and retained with the process over an extended period of years. This is the essence and key of the operation.

B. Overall Personnel Estimates

Table 2 presents detailed estimates of total numbers and types of personnel required. They were developed in the course of analyses of various functions and subfunctions, then added and classified in an appropriate manner. They reflect the requirements for the orderly design and development of a ballistic missile with the characteristics described in the introduction.

Crucial professional personnel are relatively few in number. Out of the total required staff of ~3,600, only five would be needed for senior management. It is further estimated that the total number of senior engineers (at least 7 yr of experience) will approximate 80, with an additional 235 junior engineers (from new graduates up to 7 yr experience) also needed. The most important segment of the senior engineering group—the design staff—in which creativity, flexibility and experience are important, could number no more than 30. Since skilled technicians will compose half of the total work force, they could constitute the most serious recruitment problem.

C. Overall Management

There is no substitute for experienced, capable leadership. A small number of able, talented and, above all, versatile managers are needed to supervise the building of facilities; the acquisition of the best open sources and establishment of techniques for critically discriminating among them; securing, training and maintaining a working team over many years; establishing general quality control procedures particularly applicable to the missile; procuring compatible materials and components in a steady flow as desired; acquiring key personnel and welding them into a functioning team; specifying tasks and delegating authority; and a variety of other interrelated tasks. To a significant extent, the management team must have the capabilities of men like Dr. Oppenheimer, Admiral Raborn and Generals Schriever, Groves, and Medaris. Men of this type can be found in industries other than aerospace or those closely related to missile development, but they are not plentiful, even in the United States. It would be a mistake, however, to believe that at least a few such individuals are not present in almost every country of the world, including those which may be characterized as partially industrialized.

Among the senior management the man chosen to have the technical directorship of the program will be a most important figure. His skills are identical with those required for the directorship of any complex industrial program incorporating design, fabrication, test and assembly. As with other members of senior management, it would be helpful (but not essential) for him to have had missile development or aeronautics experience. But more critical than this would be a need for versatility, a sense for engineering detail and that indefinable quality which makes for creative industrial administration.

D. The Chief Designer and the Design Staff

Design is crucial to the program and the man selected as chief designer will be somewhat handicapped if he has not had design or development experience in rocketry. In the United States most organizations which successfully organized ballistic missile development programs during the 1948 to 1960 period drew upon experienced aeronautical engineering personnel from existing aircraft industries. Nevertheless, an important conclusion of this study is that a talented, versatile, imaginative engineer with a special flair for translating physical functions into engineering devices and who has a talent for organization and the welding of an effective team to perform a demanding series of jobs, can satisfactorily fulfill the design responsibilities even though he has had no specific experience in ballistic missile design. Obviously, the more relevant his experience, the greater will be savings in time and expense.

It must be emphasized that the chief designer has heavy responsibilities. Design changes with all their

interrelationships must be formulated by and through him and his staff: they must make the changes, supervise them, help in the development of materials, participate in the static and test flights, help solve fabrication difficulties, devise possible breakthroughs, and many other tasks—all with the active cooperation and involvement of other organizational components of the staff. The design staff in missile development has a key role in achieving the important union among design, development and production aspects. Their importance cannot be overestimated.

To assist him directly, the chief designer will require some 30 senior engineer/scientists, and perhaps 60 junior engineers. These must have a talent for translating comprehensive and detailed functional requirements into working hardware.

E. Senior Engineering Staff

It would be highly desirable for the chief engineers and their immediate subordinates in charge of fabrication, test and assembly, etc., to have had extensive experience in industrial management, as well as substantive experience in their fields. The chief engineer for fabrication and industrial operations, e.g., should have had extensive experience in the fabrication of heavy manufacturing equipment (and ideally of large rocket frames)—with all involved therein in handling facility layout and requirements, inventory control and production scheduling. The same considerations apply as to the qualities necessary for the senior management, technical director and chief designer and design staff: good theoretical education and practical experience as well as personal qualities such as flexibility, the ability to adjust to the requirements of a wide variety of dissimilar operations and a flair for precision operations.

It is an essential point that the level and nature of work in fabrication, materials, and other of the basic development and fabrication portions, even engine and propellant development, is of a different order than the responsibilities of the management and design staff: it is demanding but much less creative, more mechanical and in many respects not especially different from ordinary industrial or engineering operations. Therefore, the specific experience and educational factors noted above, though highly desirable, are not crucial.

F. Junior Engineers

Of the ~235 junior engineers who would be required, it could suffice if they had a good engineering education and experience in precision manufacturing. Mechanical and electrical engineering would be the most desirable disciplines, but personal qualities like flexibility and versatility could again prove much more important than a particular major in engineering school. A good civil engineer could as easily become an outstanding contributor to solving fabrication problems as a mechanical engineer, if he possessed the desired qualities.

G. Skilled Technicians

It is paradoxical, but experience may be more essential and more difficult to secure among technicians than among professional engineers. The background of the latter being academic and systematic, they could probably be trained with relative ease. There is, however, no traditional school for technicians in military missile development, and a great deal of time and effort will inevitably be spent in training. It will probably be the design staff, along with numbers of engineers with whom they have successfully established rapport, who will be responsible for this training. There will be no substitute for time and application. They must learn, e.g., how to operate mixing vats, to establish and maintain proper quality control tests on chemicals and run many other types of unfamiliar tests in a uniform fashion. Many operations involving packaging cannot be learned, except through trial and error, and there will be a very large requirement for maintaining—without failure, for failure will bring heavy penalties—unusual and unfamiliar equipment and materials.

H. Unskilled and Semiskilled Labor

Approximately one-third of the total force will consist of such personnel, half of whom will be utilized in fabrication. In contrast to recruitment problems encountered in relation to skilled technicians, few partially industrialized countries would have difficulty in obtaining and training these personnel for the functions required.

I. Administrative Support

It is estimated that ~40% of the total work force must inevitably consist of administrative personnel responsible for financial management, procurement, personnel recruitment and administration of material services, and similar operations. The importance of these requirements, if not their difficulty, ranks with that of the general management and design. The quality and experience of certain administrative personnel and the degree to which they can work closely and effectively with top management and the design staff will be of crucial importance.

As indicated in Table 2 some 150 professional administrative personnel would be required, with 30 of these in the senior administrative category.

J. A Note on *Crash* Programs and Personnel Requirements

It has often been noted that industrial development time can be reduced by the institution of certain emergency measures. These may include the expensive expedient of simultaneously pursuing several approaches to the solution of a particular problem. These programs are also often characterized by a tightening of schedules, by prevalence of an *emergency* atmosphere, and by trying to elicit much greater personnel efficiency through the establishment of various incentives. Often personnel and other resources (with little regard to cost) are multiplied well above the level of the comfortable minimum required to complete the work in a reasonable period.

However, in a ballistic missile development program, the size and composition of the staff required is a function of the work to be performed. Particular concepts, skills and effort are required before the program can become reality. The work must follow an objective, structured flow of events channeling the application of necessary resources. These steps may be modified or somewhat compressed, but such actions are limited in number and application.

Nevertheless, it is to be expected that some concurrency will be attempted—and this makes good sense from an engineering development point of view. If a country can afford it, there are obvious advantages to working out alternatives simultaneously rather than serially.

VIII. Component Requirements and Industrial Base

A. Components List

Appendix B of the full report presents a comprehensive list of components, subcomponents, materials and other items which could be used for military missile development and which also may have application in peaceful space programs. The function of each item is described, and information, relating to general or relative availability and the extent to which the item is used in ordinary civilian production is also presented. Although many of the items relate to advanced rocketry applications, e.g., inertial guidance systems which are not necessarily needed for the military missiles discussed in this study, it must be emphasized that many items permit substitutions. The range of design alternatives is very great. It should also be noted that most of the materials on this list are items normally available on the world market and are comparatively simple to obtain or manufacture. Nevertheless, the number of components is great—a factor which necessitates efficient handling of a complex procurement program, and careful attention to compatibility of components procured from a variety of sources.

B. Requisite Materials, Components, and Industrial Base

In attempting to deal with the question of the industrial base necessary to develop simple missile systems, it is most realistic to assume that since a very large proportion of the basic components and materials required are freely available on the world market, a partially industrialized country, assuming it had the necessary hard currency, would proceed to secure them during the process of development. This would be true especially for such electronic components as resistors, capacitors, transistors, as well as for certain metals such as steel and other items like kerosene and a variety of ordinary manufactured products like nuts, bolts, bearings, and gears. It is considered, therefore, that there would be no real need for a partially industrialized country to have a particularly large industrial base. The domestic requirements include those components which cannot be secured from abroad and a financial and general economic base sufficiently large, efficient and well integrated to absorb the level of general economic and industrial activity required to develop missiles over a period of years.

It is not difficult to postulate a small country, not possessing a large industrialized base, ably absorbing the economic cost of both development and deployment of "primitive" military missiles given the motivation, and provided that it had sufficient finances and the requisite types and numbers of personnel. As indicated above, one of the crucial factors is that the missile development process is to a significant extent one of learning by doing through the application of talent and persistence. Certainly the presence in a country of a high degree of motivation, a moderate rate of literacy, and of political and social stability could make for rapid progress.

What is important to establish is that perspectives on the nature of the industrial base required are similar to those for experience in missile development and design—the more there are present, the greater the ease of organizing and maintaining the operation and the less will be the amount of time and effort required. The more industry there is, the larger will be the skilled labor pool and the easier it will be to train technicians and other members of the staff. It is suggested, however, that the essential industrial requirements for missile production

which a country would need to have within its boundaries are foundries, ordinary machine shops, and probably precision machine tooling. The rest could be fabricated and developed in time, given the motivation, effective management and adequate funds to provide for a regular flow from abroad of the necessary basic materials.

The critical requirement which must be fulfilled by some sort of industrial experience is the provision of skilled personnel, particularly at the technician level. There are several manufacturing and assembly operations which require special talents in addition to one overall need—quality control.

1. Guidance and control elements

The most difficult aspect of guidance and control is integrating the system. Simple components are normally available on the world market and are used for a variety of other functions. Packaging of guidance and control assemblies requires sheet metal working capabilities, e.g., casting, forging and welding, with special welding emerging as a typical difficult skill to be learned. Even vibration test systems, whether for a 1500-lbf or for a 30,000-lbf—the latter being required for complete guidance compartment assembly—could be fabricated, were there available high precision machine tooling.

2. Propulsion

Basic materials for a typical liquid propellant would be common commercial products; e.g., kerosene. As on-site oxygen generators are far from uncommon in steel plants all over the world, there need be no particular difficulty with liquid oxygen. As for kerosene, the largest liquid system considered in this context requires less than 80,000 lb of propellant. This means about 40,000 lb of kerosene. Assuming a hundred test firings, ~2000 tons would be needed—considerably less than the cargo of a typical tanker. Only nitrogen tetroxide, a liquid oxidizer, and ammonium perchlorate, a solid oxidizer, and hydrazine, a liquid fuel, do not have standard commercial applications.

Mixing and curing equipment for solid propellants would require special machinery, which is, however, currently available on the open world market. Heavy machine tools can be easily purchased relatively inexpensively, and only practice and application would be necessary to bring into being the individual skills required for using them.

For the tanks or cases of various propellants, metal-working common to many industrial applications is required, though some special tooling might be needed for forming, clamping and welding large diameter and thin-walled tanks. Special tooling again could be acquired from abroad.

Most of the valves and plumbing necessary for a liquid propulsion system are sufficiently commonplace to be purchasable as standard items from chemical industries in the open market; only thrust termination valves and turbopumps stand out as relatively difficult items, but these, again, can be manufactured if there is, in the country concerned, adequate machine tooling. The nozzle and thrust chamber fall into the same category; the question of an industrial base which is more than modest does not intrude. Materials are ordinary and the quantities small.

3. Airframe

The basic requirements relating to the airframe are for metal-working skills and tools which generally exist in ordinary machine shops as they have been found in the United States over the last generation and as they are commonplace in most parts of the world. Most of the basic raw materials for airframe construction, such as sheet stock, tubing and casting alloys are readily available on the world market in the quality and with the properties required for the posited missiles. They would, of course, have a wide variety of other uses. Metal-working and assembly facilities would be those required of a normal industrial use.

As for floor space, it might be noted that the *Thor* required ~150,000 ft² and the *Pershing* ~500,000 ft². The performance of the *Thor* exceeded that of the posited missiles, and it would be reasonable to assume for this context of this study 100 to 200,000 ft² of floor space. For ease of administration, it could be at one site, but, could instead be divided among smaller separated factories of 10 to 20,000 ft² each.

Bearings and gears required for airframe construction are commonplace and readily available on the world market. The same is true for electrical and hydraulic components like motors, batteries, power supplies, relays and switches, which are standard and available on the open market.

4. Ground support equipment

Preparation of the test range and launch equipment and military launch site will not place significant demands on a country's general industrial base. Most of the large structures, such as the launching pad, service

structure, umbilical tower and blockhouse, are built with ordinary construction techniques used in standard steel or concrete buildings and bridges. Instrumentation for ground support is generally of a nature which has other commercial uses. It not purchased abroad, it could be constructed more easily than instrumentation for the missile itself, since there are no restrictions as to weight, size, or power consumption. If they must be produced, they can be fabricated in a modest metal-working machine shop of the most basic nature.

A few special materials like tungsten, are required in the the airframe. Even they, however, are readily available as standard commercial products. When, as in the case of the preparation of ablative materials for the nose cone, should this be needed, there is no requirement for an industrial operation which could produce it quickly, because it would be required towards the end of the development process. For heat-resistant materials like jet vanes, the primary problem is quality control. This applies even for materials like graphite blocks. The principal problem is testing a number of possible materials during the static firing program. Once selected, however, there is little specialized training and very little specialized machining needed to make these components.

IX. Financial Requirements

A. Personnel Costs

Assuming a well-run, amply supported, and reasonably conceived design and development operation for the 1500-mi missile, as described in the body of this report, the personnel costs will run between $100 to $200 million (with $180 million as a typical figure) over the 10 yr period specified. These figures, based on a total staff of ~3,600, were developed following a cost analysis of the personnel requirements noted in Table 2 and in Fig. 5. During this analysis certain considerations were kept in mind: (1) salaries and wages for all categories of personnel in a partially industrialized country, would be at a considerably lower level than in a more developed country, and (2) lower efficiency levels (i.e., man-hours required to complete a specific job), and a longer training period than would be the case for a more highly industrialized country would be expected.

B. Costs for Material and Component Purchases and Facility Construction and Maintenance

Rather than attempting to quantify these costs arithmetically, the approach used in this study has been to derive a workable ratio between personnel costs and all others. Following consultations with experienced senior personnel at the Jet Propulsion Laboratory, the Rand Corporation, the Stanford Research Institute, and several aerospace companies, a range of estimates has been developed, which indicate that these other costs, in the United States' experience, has varied from three-quarters to double the personnel costs, with a rough consensus on the use of a 1:1 ratio. A utilization of these factors, in conjunction with United States' personnel costs (following typical U.S. salary levels and the requirements noted in Table 2) would evolve a figure for these other costs which would lie somewhere between $250 million and $700 million, with perhaps $350 million as a typical figure. Since these latter figures, in an absolute sense, would also apply to a partially industrialized country, it is thus estimated that the cost of the entire program for the partially industrialized country will be within the range of $350 million to $900 million, with perhaps $530 million being typical, if one assumes the typical non-personnel cost figure ($350 million) and the typical personnel expense figure ($180 million). Assuming two additional years for the production of the assumed force size, an additional financial burden of perhaps $30 to $50 million should be expended.

These figures (Table 3) indicate the prosecution of an efficient program, but give allowance for mistakes and difficulties. As indicated earlier, the cost would be somewhat less if a 300-mi missile were posited, or if development time were shortened through the importation of nonnational personnel.

Table 3. Range of cost estimates, in $ million

All other costs	Personnel costs for 10-year period		
	$100 Low	$180 Typical	$200 High
Low: $250 U.S. ratio = 0.75:1.0	$350	$430	$450
Typical: $350 U.S. ratio = 1:1	$450	$530	$550
High: $700 U.S. ratio = 2:1	$800	$880	$900

An examination of these figures, which are given in $ U.S., should take into account a wide range, in these countries, of availability of hard currencies (such as $ U.S.), which would probably be necessary to purchase many components on the open world market. As this report does not deal with a specific country, no attempt has been made to translate these figures into meaningful statistics within the financial context of a given country (i.e., relationship to trade balance, GNP, percentage of

DEPLOYMENT CATEGORIES [a]	DEVELOPMENT PERIOD, yr										PRODUCTION PERIOD, yr [b]	
	1	2	3	4	5	6	7	8	9	10	11	12
Management	5	5	5	5	5	5	5	5	5	5	5	5
Administrative	300	900	1300	1450	1450	1450	1450	1450	1450	1450	1300	700
Design	190	190	190	190	190	190	190	190	190	100	50	50
Facility construction	1000	1000	1000	1000	600							
Propulsion and engine		100	350	600	650	685	685	685	685	685	685	300
Guidance and control		100	100	300	400	450	517	517	517	517	500	250
Airframe				100	140	160	200	246	246	246	246	120
Ground support equipment			300	350	400	500	546	546	546	546	500	300
SUMMARY, man/yr												
Administrative	300	900	1300	1450	1450	1450	1450	1450	1450	1450	1300	700
Technical and management	195	345	945	1525	1785	1990	2143	2189	2189	2089	1986	1025
Construction	300	1000	1000	1000	600	–	–	–	–	–	–	–
Total	795	2245	3245	3975	3835	3440	3593	3639	3639	3539	3286	1725

[a] Systems and Flight test personnel are included in other categories.

[b] A two-year production and checkout period is postulated, during which the total missile force will be prepared.

Fig. 5. Personnel deployment schedule

total national budget, percentage of total defense budget, or percentage of total research and development budget).

X. Peaceful Space Programs and the Development of Military Missile Capabilities

To determine the extent to which the development and manufacture of equipment needed for the prosecution of peaceful space programs could help, in terms of the accumulation of personnel skills and resources, in the development of a military ballistic missile program, four representative types of space programs are considered: (1) small sounding rockets, (2) large sounding rockets, (3) vehicles which are capable of placing a satellite into Earth orbit, and (4) scientific instrumentation for space vehicles. All of these projects are assumed to be carried out within the country in question, as would a military missile development project. On the other hand, if a given country (partially industrialized) obtains this equipment through purchase or gift rather than through its own design, development and manufacturing process, obviously, the *degree* of advantage relative to their eventually utilizing this knowledge and capability in developing military ballistic missiles will be considerably lower than if they were to carry out the development effort themselves.

A. Small Sounding Rockets

Included in this category are unguided rockets using solid propellant engines, in both single- and multiple-stage configurations. Typical weights range from 100 to a few thousand pounds. Payload weights range from a few pounds up to perhaps 100 lb, with the achievement of peak altitudes ranging from perhaps 20 to 30 miles for the smaller version to a few hundred miles for the larger ones.

A development project for such rockets would result in the accumulation of certain special capabilities, particularly in the area of solid propellant engine technology, which would be quite useful in the development process required for military ballistic missiles. In this area, the difference between the small sounding rocket and the larger military rocket is one of magnitude, rather than method. There would also be a contribution in the area of electronic instrumentation, principally in the techniques of telemetry and tracking.

Equal in importance to the accumulation of technical expertise would be the acquisition of personal experience by a number of scientists and engineers. These individuals would have accumulated extremely useful experience in working with government officials, in evolving critical quality control measures, and in establishing complex procurement lines with suppliers of basic materials and components. Thus, even though the overall staff size necessary for small solid rocket programs would be perhaps only 5% of that required for a military missile program, these few individuals would have direct relevance considerably greater than would appear from their small absolute number. Logically, these individuals could form the core technical and administrative team for a military missile effort.

B. Large Sounding Rockets

The overall weight of these rockets varies from a few thousand to several thousand pounds. Solid propellant engines are typical, but, some now in use, such as the *Aerobee*, utilize liquid propellant stages. In this discussion it is assumed that the rockets would have an attitude control system for directional guidance, but no velocity control capability. Payload weights would vary from 100 to perhaps 300 lb, and peak altitudes would be a few hundred miles.

One of the typically smaller of this group is the *Aerobee*, usually employing a liquid propulsion engine in the sustainer stage. This rocket generates some 4000 lb of thrust and launches a 150-lb payload to an altitude of 150 mi. One of the largest sounding rockets is the *Athena* with a thrust of 122,000 lb, and which can launch a 300-lb payload to an altitude of 500 mi. Its two-stage version, especially with respect to performance characteristics, is similar to Model 4, discussed in this study.

In the course of a program to develop such rockets, technologies required for propulsion and airframe development would be considerably advanced (as compared to those needed for small sounding rockets), as would some aspects of the technologies required for guidance systems. In addition, launch facilities and test procedures, typical of those required for a military missile program, would be created. In general, the size of these rockets is still smaller than those required for the military missiles considered here, except for the 300-mi range model. A complete guidance system necessary for the military application would not be developed, although several necessary components, together with a number of important skills, would be made available. It is estimated that about half of the skills, resources and components required for military missile development would be attained in the course of such a program.

The staff required would represent, in terms of numbers alone, about 15% of that necessary for that type of military ballistic missile project described in this study. However, as in the case for the small sounding rocket program, the type of skills and experience generated would be concentrated in the crucial senior management and senior engineering groups. It is estimated that the availability of a staff with this experience would have the effect of providing almost half of the required personnel at these levels for the military program.

If, in a given country, there should occur the successful completion of the development of large sounding rockets of the type considered here, and, if in such a country consideration was then given to the possibility of continuing into a military missile development program, it is a conclusion of this study that they could look forward to an additional task, the difficulty of which would be very nearly the same as the difficulty of the one already completed. Such a situation would affect not only the decision to proceed, but also the likelihood of success.

C. Satellite Launching Vehicles

A satellite launching vehicle, with the capability of placing a 50- to 100-lb payload into an orbit a few hundred miles above the Earth, would also have the performance capability of launching a 1000-lb payload over a 1,500-mi range. Thus, the successful development of such a vehicle would indicate considerable progress toward the development of a military missile capability. Propulsion system development problems would have been completely solved, and substantial progress made toward the solution of a guidance system adequate for military requirements. In fact, if it were desired to maintain control over resulting orbital parameters, the resulting guidance system would also be suitable for use in a military system.

It is likely that fewer missiles would be produced in the course of a satellite launcher development than would be required in the course of a military missile system development. This implies that the total work force and facility development would be less than military system requirements. Also, certain aspects of launch procedure would not be developed to the point where they would be militarily useful. Thus, even after the successful completion of a satellite launcher development effort, additional work would be necessary before a military missile could be considered ready for deployment. Nevertheless, this additional effort would be small compared to that already

completed, and it is concluded that it would be a simple step to proceed from one to the other. It would require a few years, but no important need for the acquisition of completely undeveloped technologies.

D. Scientific Payload Development

In several countries, which do not now possess an independent rocket capability, scientists are developing instruments for inclusion in satellite or sounding rocket payloads. In some cases, complete payload systems are being developed. Such undertakings will involve the gaining of experience with certain aspects of missile technology, power supplies, instrumentation, and certain types of electromechanical systems. However, large areas of missile technology such as propulsion, guidance, and vehicle airframes and structures would be completely untouched.

It is concluded that the experience gained would make a slight, almost negligible, contribution toward the capabilities required for the military missile development system. Nevertheless, it is likely that the specific individuals involved with such a space science program would be incorporated at certain key positions in any subsequent missile development team. But their availability, although helpful, would not be crucial. They would bring into the task some experience in working in concert with government agencies, procuring equipment from abroad, developing certain types of electronics systems, and operating quality control and test procedures.

E. Conclusions

A space science program, limited to the development of instruments or payloads to be launched by rockets provided by other countries, would make no significant contribution to the development of resources or personnel required in a military missile development program. In contrast, the successful development of a satellite launching vehicle would make available most of the resources and technical personnel needed for the military effort. In between these two extremes is a wide spectrum of possible development activities aimed at peaceful space exploration, which would make certain contributions toward the required level of technology. It is judged that the midpoint of the spectrum is characterized by a development of a large attitude-controlled sounding rocket. These judgments are summarized numerically in Table 4.

Table 4. Summary of the effects of space programs on the capability to develop military missiles

Program	Effect of personnel	Effect of component and facility developments	Time saving (from 10 yr program)
Small sounding rocket	15% to 20%	20%	1 to 2 yr
Large sounding rocket	30% to 40%	50% to 60%	3 to 4 yr
Satellite launcher	>90%	>90%	7 to 8 yr
Instrumented payloads	<5%	5% to 10%	<1 yr

[redacted]

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